Progress Report

Grant #731009
Ultra-Efficient Generators & Diesel Electric Propulsion
Genesis Machining & Fabrication
Reporting Dates: 10/2013-12/2013

Deliverables Submitted:

We are submitting the 15 kW genset test results and initial motor efficiency test results.

Budget:

We are invoicing for $13,125 for labor, $11,911.62 for materials, equipment and other expenses. We are requesting $4375 in advance for labor during the Jan-March quarter of 2014. Finally, we are submitting $53,840.44 in match.

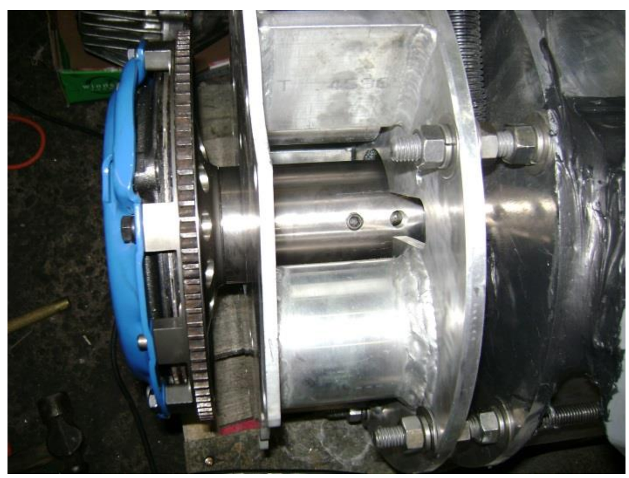
Schedule Status:

We are on schedule.

Work Progress:

1. Yet higher power EV motor and inverter testing

The first task this quarter was the installation of a higher performance clutch into our EV test-bed. We had an ongoing problem with vibration above 3000 RPM which prevented power testing above 83 kW. We also had trouble with a low resolution shaft encoder which caused poor performance when starting in gear and at the bottom end of regen braking. We remedied the problems by building a new motor coupling, installing a racing flywheel, and using a ring-gear as our shaft encoder.

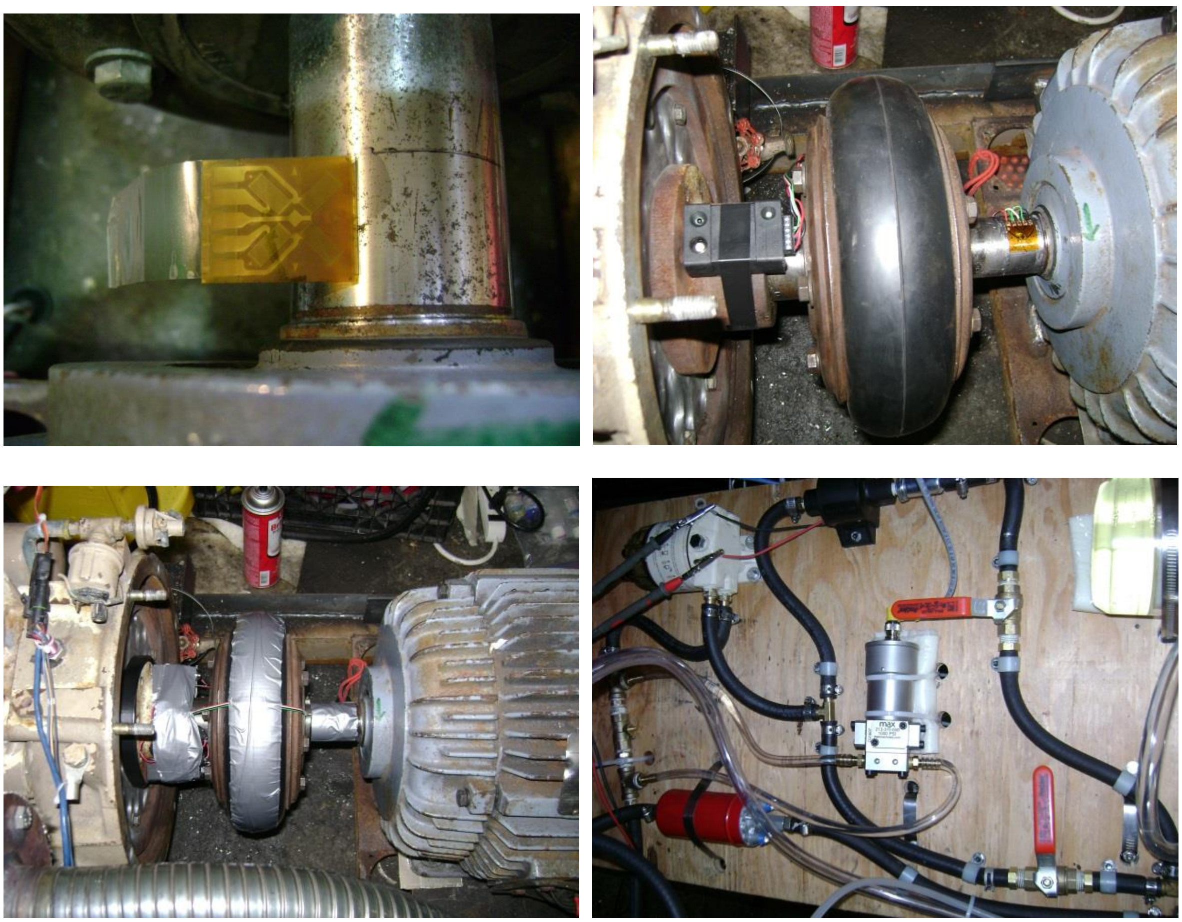


Precision flywheel coupling and racing flywheel and clutch attached to EV motor

After this installation, the FPGA motor control code was updated to handle the higher resolution gear-tooth data and the vehicle was tested. This time we were able to pull around 120 kW during a test drive. The limiting factor for this test was the poor condition of the Kodiak roads. We are now able to spool the motor to 4500 RPM but are having sensor accuracy issues above this speed. We will look for a better gear-tooth sensor in the future but have solved our power testing problem for the time being. The new setup also solved our low rpm and regen braking issues.

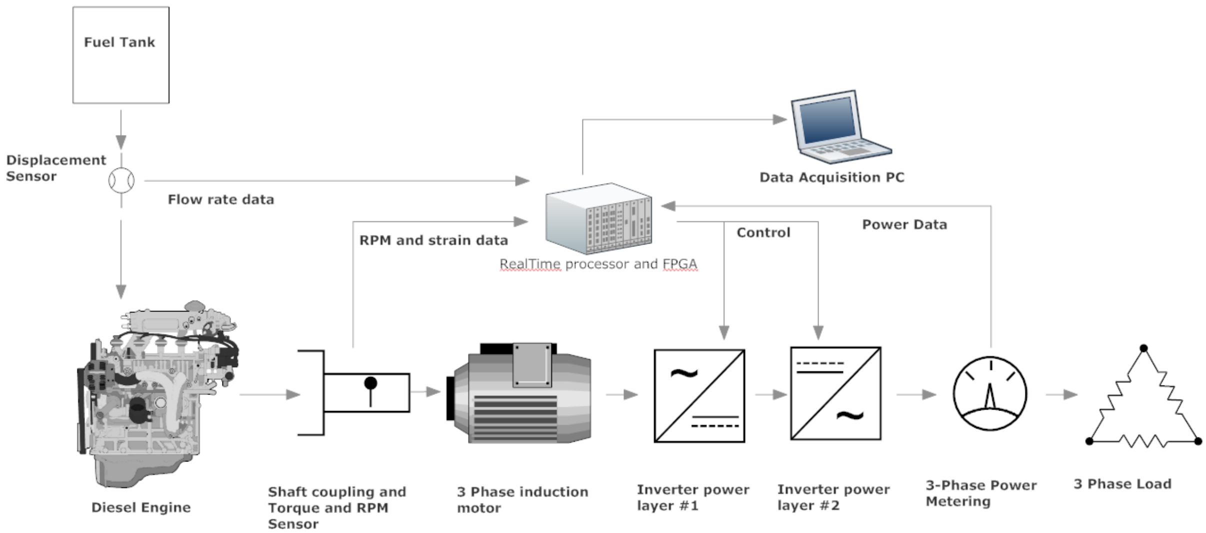
2. 15kW Genset Testing

During this quarter we continued our 15 kW proof-of-concept variable speed generator testing. We built on the results from last quarter by installing a precision displacement fuel meter, calibrating our inverter power measurement variables, installing a shaft torque sensor, and producing Brake Specific Fuel Consumption (BSFC) maps for the operating space of the engine.

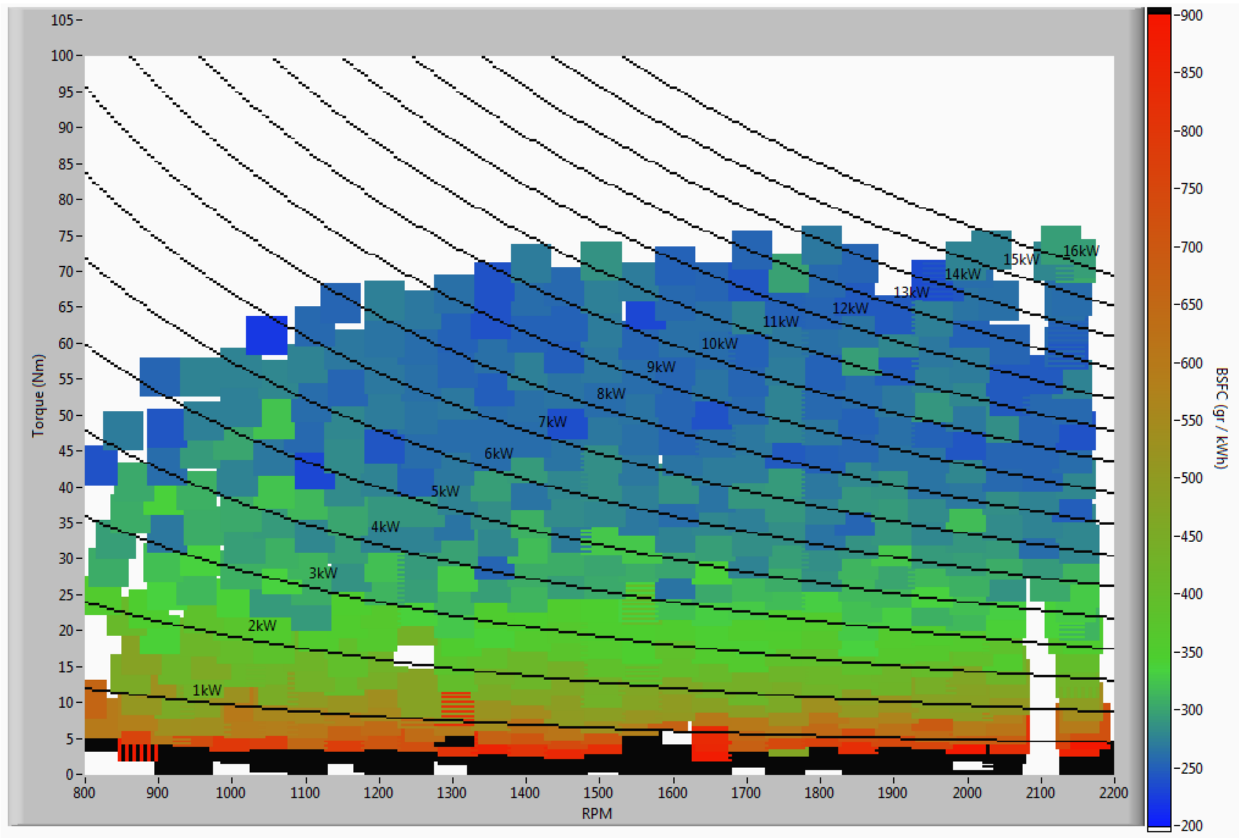


TR: Strain gauge, TL: Gauge wired to RF transmitter, BR: strain gauge secured in place, BL: displacement fuel meter in-line with engine

The following flowchart illustrates the experimental setup. The system was professionally calibrated by an engineer from Alaris, LLC using a Hioko 3197 Power Quality Analyzer. Calibration was considered complete when correspondence between the PQA and the Data Acquisition PC was shown for the entire power range to be studied.

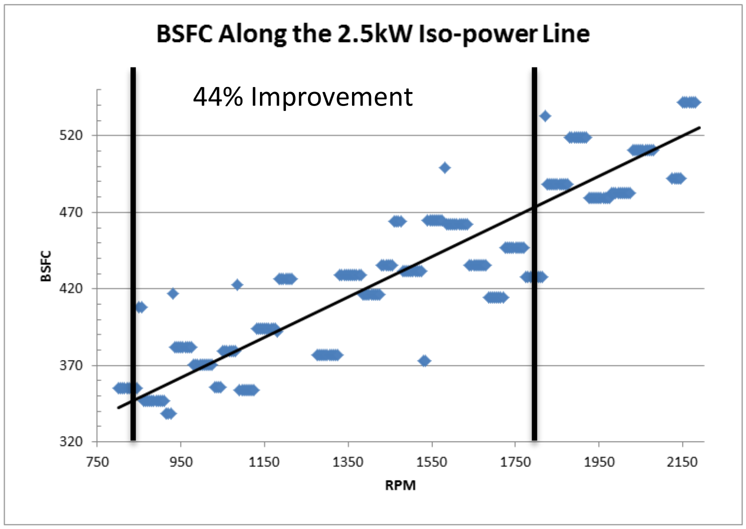


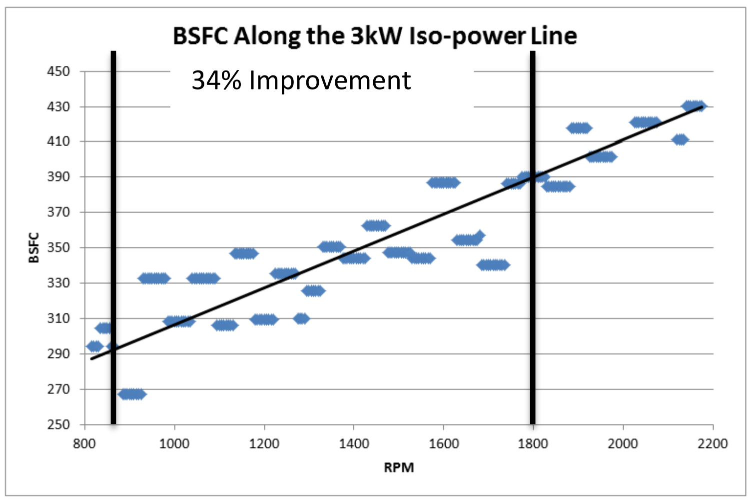
The system is calibrated using a Hoiki 3197 Power quality analyzer. Linearity was shown for the entire power range tested.

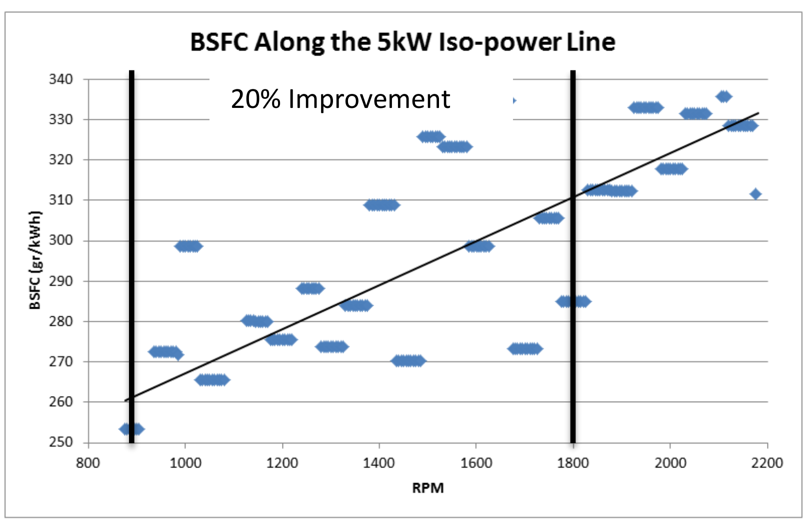


Brake Specific Fuel Consumption (BSFC) map for the operating space of the genset. This is a naturally aspirated diesel and does not have the “sweet spot” typical of turbo-charged diesels.

Samples of BSFC were taken along the 2.5kW, 3kW, and 5kW lines respectively to show the increase in efficiency when the engine is throttled down. The results (shown below) were 44%, 34%, and 20%, respectively for an engine throttled back from 1800 RPM to the most efficient RPM available. The scatter plots reveal the noise from the displacement fuel sensor. This is attributed to the operation of the mechanical lift pump of the engine, small amounts of static air in the fuel line, and fuel hose flexing. Cleaner data is possible by using hard fuel lines and longer data acquisition periods. Each sample in this BSFC chart was only 10 seconds long. We also recommend updating the fuel meter to have a quadrature encoder rather than the simple frequency encoder. This will allow it to detect any reverse flow caused by pump operation.

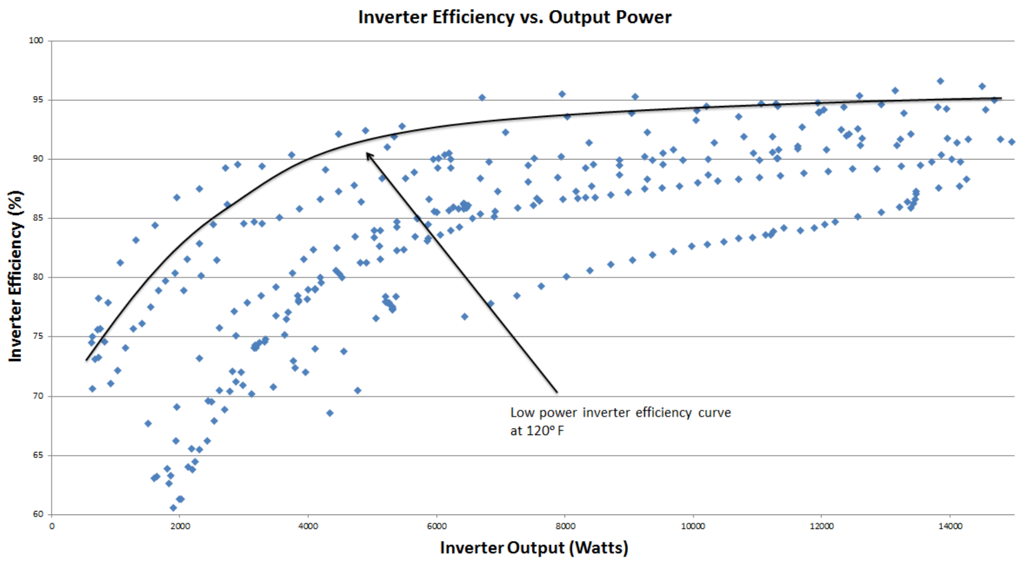

BSFC Along the 2.5kW Iso-power Line
44% Improvement
520
470
420
370
320
750
950
1150
1350
1550
1750
1950
2150
BSFC
RPM

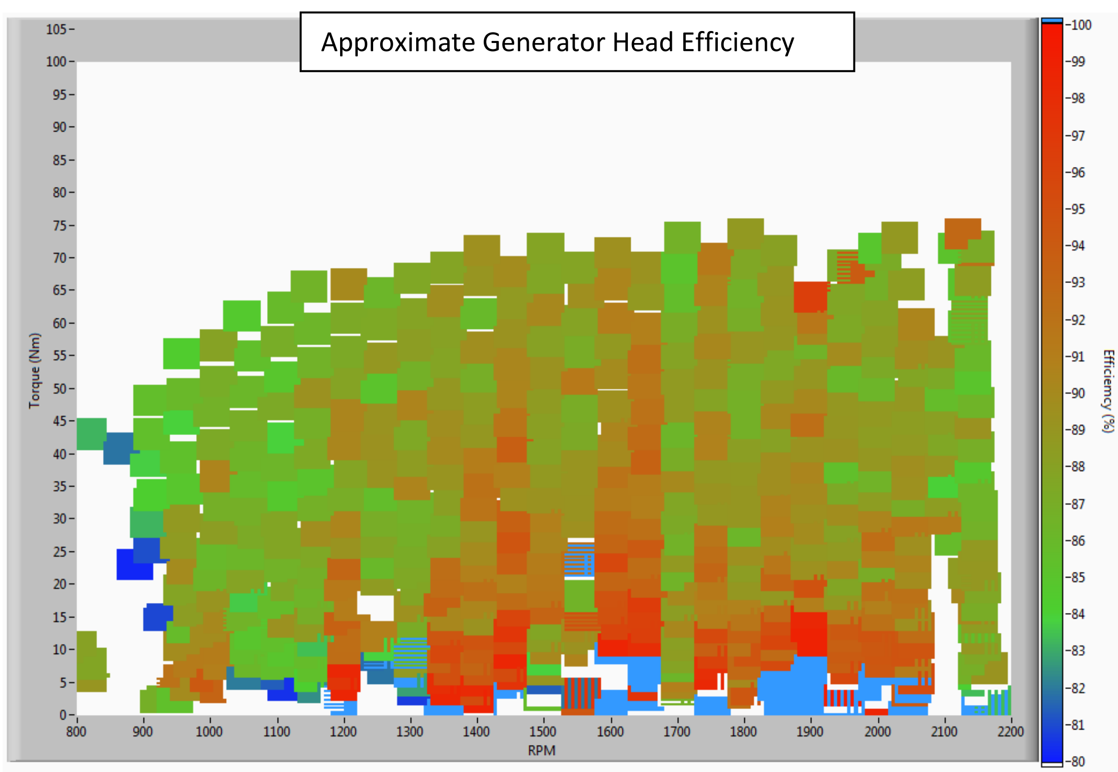

BSFC Along the 3kW Iso-power Line
34% Improvement
450
430
410
390
370
350
330
310
290
270
250
800
1000
1200
1400
1600
1800
2000
2200
BSFC
RPM


BSFC Along the 5kW Iso-power Line
20% Improvement
340
330
320
310
300
290
280
270
260
250
800
1000
1200
1400
1600
1800
2000
2200
BSFC (gr/kWh)
RPM

Generator Head Efficiency:

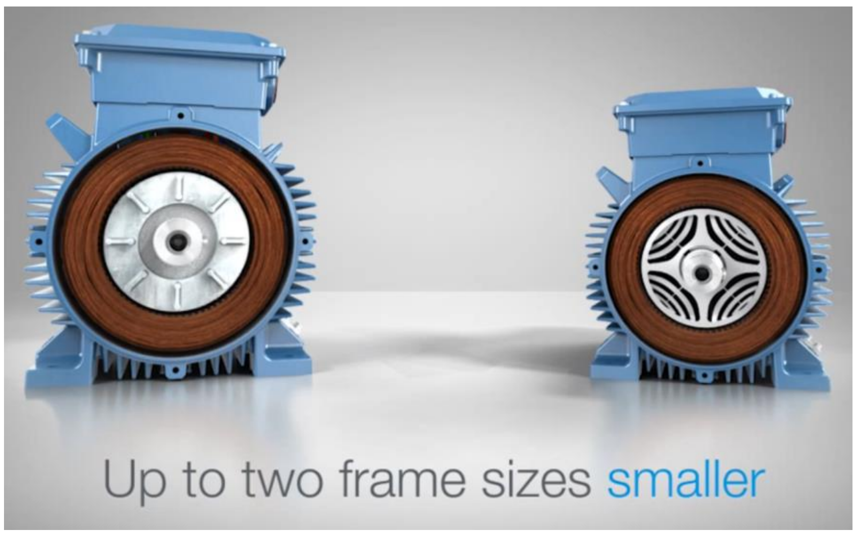
This study was limited in that the generator head efficiency could not be directly studied. This is because only the output power layer of the inverter actually had current and voltage sensors to make power measurements. So, the total efficiency of the inverter and the generator head could be measured, but not the motor efficiency by itself. To compensate for this a conservative estimate of 93% inverter efficiency was made from the graph below, and the raw combined efficiency data was offset by 7%. Please note that inverter efficiency rises to 98% above 20kW.





As can be seen from the efficiency map, the motor efficiency ranges from around 85% to 97% over the whole operating space. We feel that these are realistic and good numbers in that 1) a typical 15 HP induction motor has an efficiency of around 85%, 2) this was an old, non-inverter ready, low efficiency induction motor. The larger inverter-ready induction machines, which we will be using in actual applications, will have higher efficiency.

Finally, we are investigating the possibility of using a new technology motor for designs: the Synchronous Reluctance Motor (SRM) made by ABB. These motors are identical to induction motors except that the rotor, rather than relying on induced currents, has paths of high magnetic reluctance. The bottom line is that the SRM's are low cost because there are no magnets, are more efficient than induction motors because there are no rotor losses, and have a higher power density than induction motors. We have purchased a 1kW SRM motor to compare side by side with a 1kW induction machine.



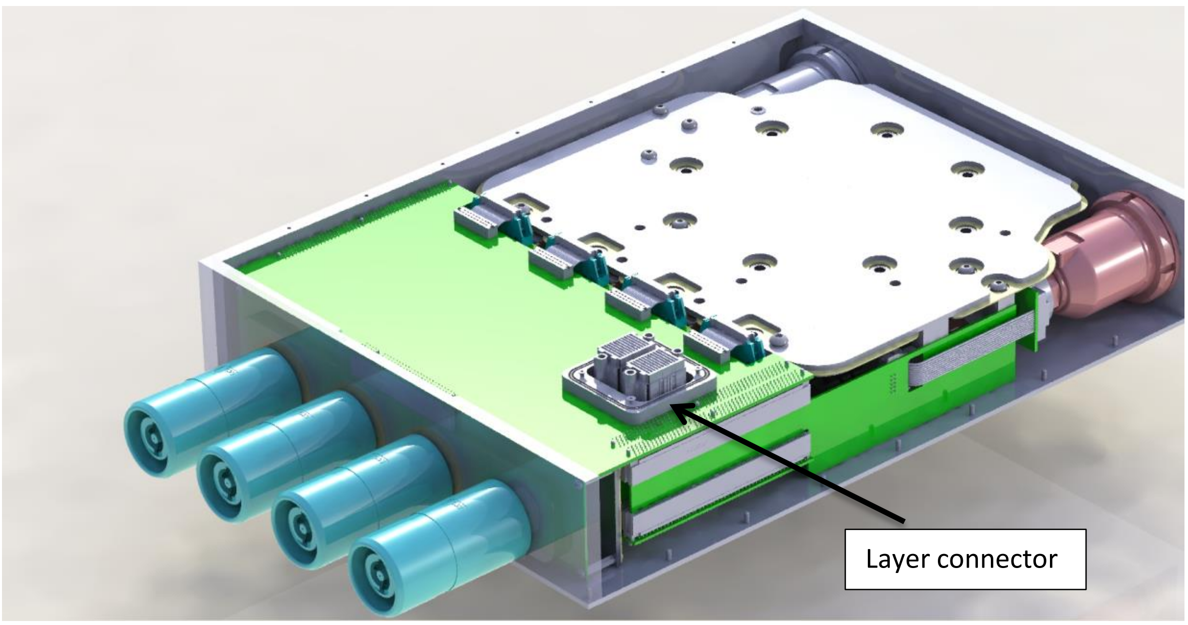
Induction motor side by side with an SRM motor: Note the radically different rotor design and the smaller frame size.

3. TRL-7

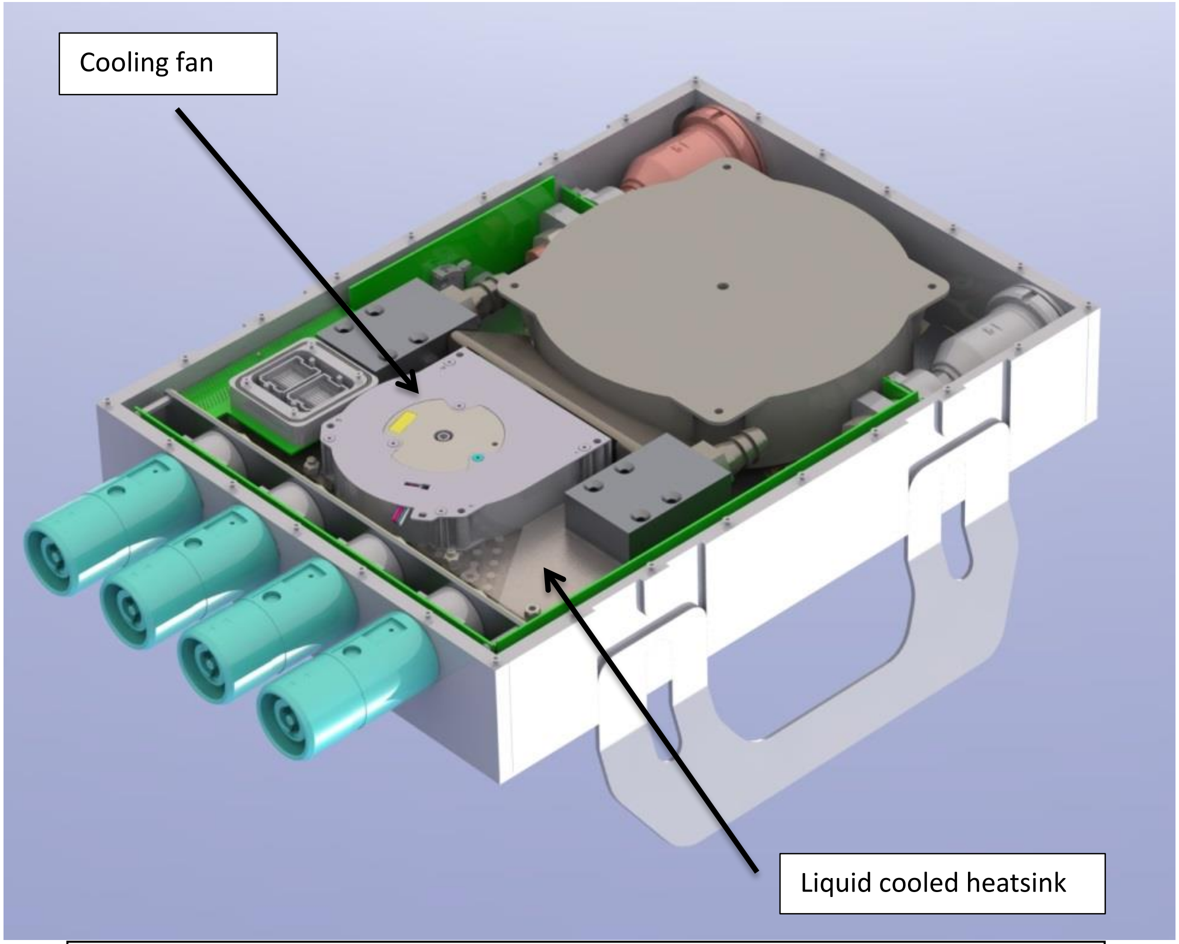
Progress: Our goal for the TRL-7 design is to have a near market ready or beta version product deployed in our Diesel Electric Bus test-bed. All parts are going to be precision machined or made with rapid proto-typing / fabrication techniques. All electronic components will be professionally printed by a PCB assembly house. Along with the actual inverter design, we are also designing the production chain: where and how parts will be built for small production volumes. We have continued our work with Worcester Polytechnic Institute and Prof. Bitar on PCB design. At this point we have all chips selected, worked out the details of data acquisition, ADC's, serial and parallel bus protocols, and mechanical layouts of the several boards that go into the inverter power layers. The

WPI group is currently testing the new data flow concepts and beginning PCB design. I will be travelling to the university to work face to face with the group to validate their work.

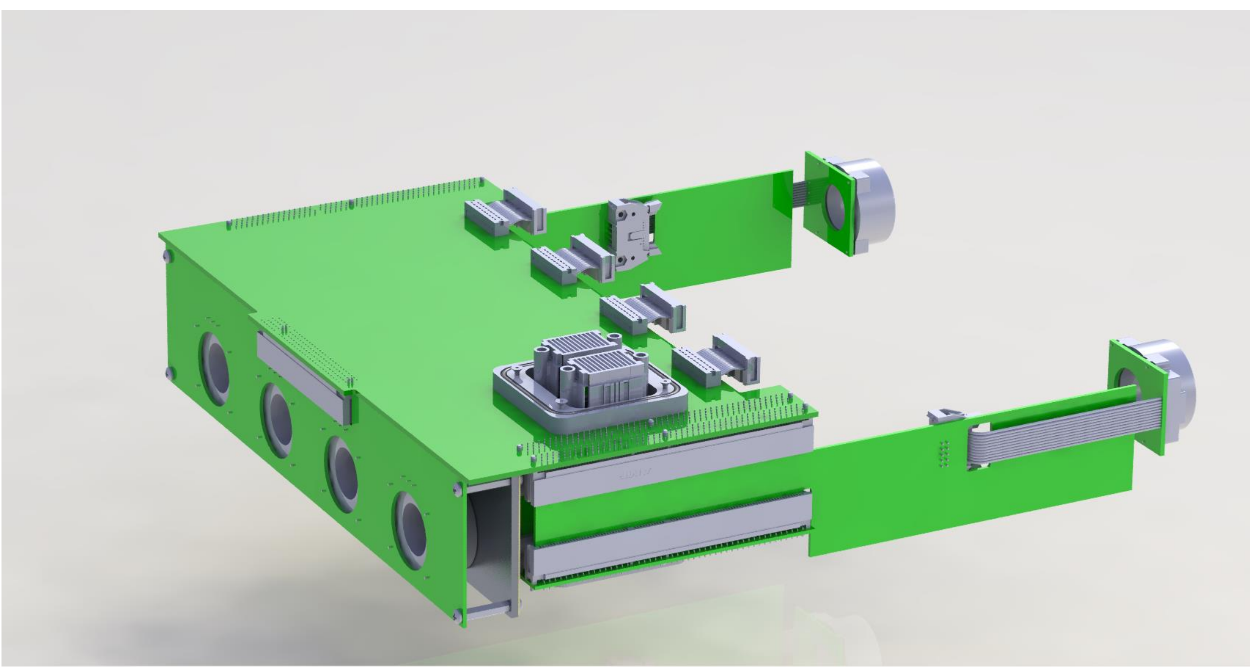
New features of the TRL-7 design included hermetically sealed power layers, unlimited stack height with control layers interspersed, redundant FPGA options, liquid-to-air laminar bus cooling, and professional power connectors from Multi-Contact. We are designing configurations for power level, capacitor pre-charge options, and sensor options. Up to four power layers can be sensed and controlled from a single control layer.



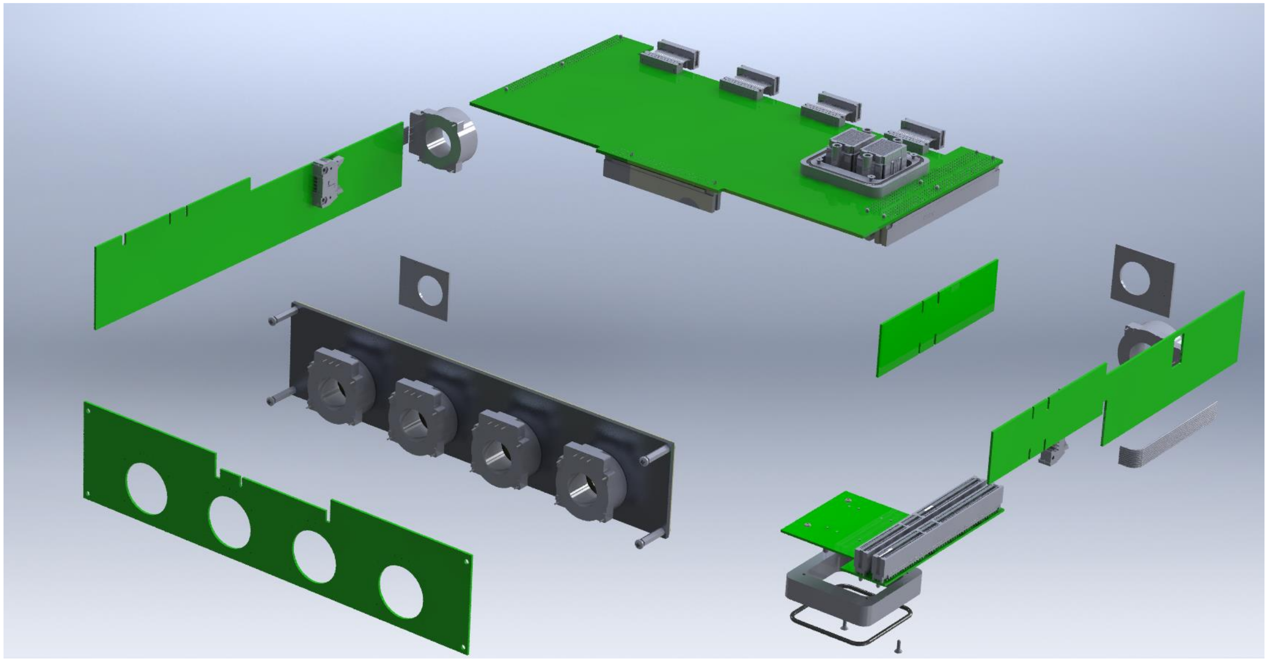
TRL-7 Inverter power layer shown with housing open. Top view.



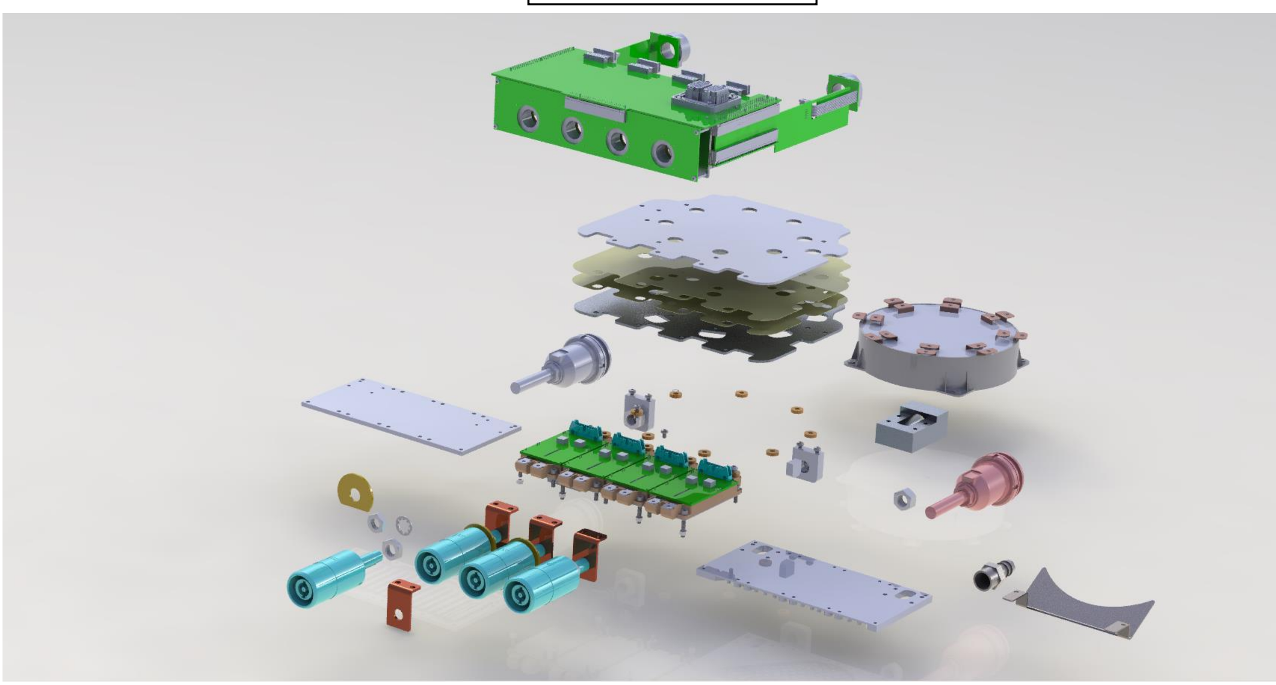
TRL-7 Inverter power layer shown with housing open. Bottom view.



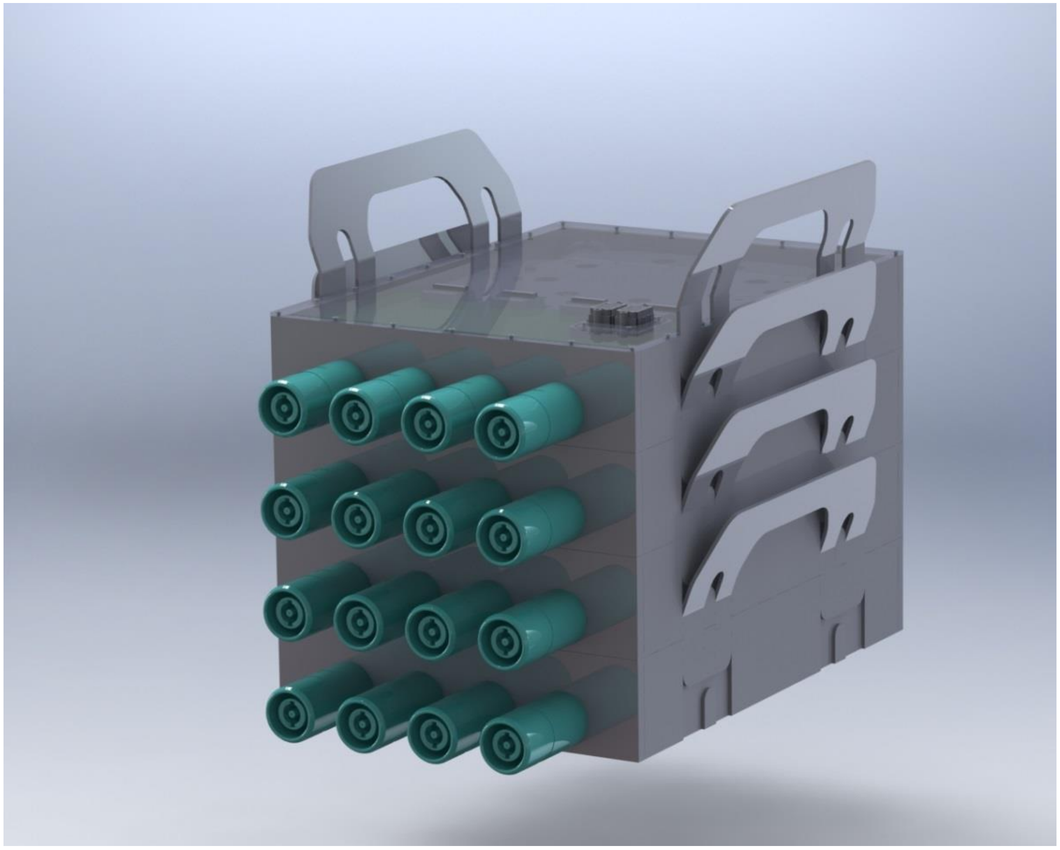
PCB's with power components and housing removed



PCB’s exploded view



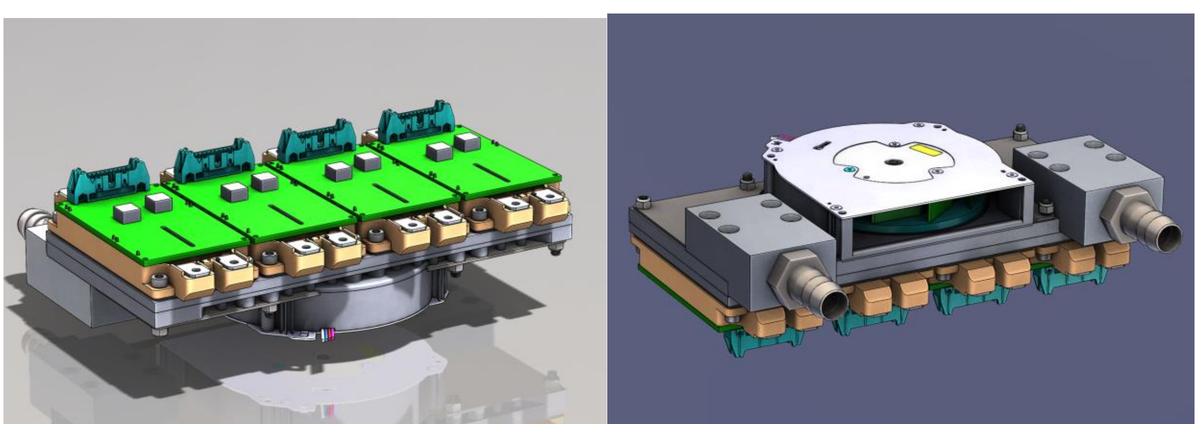
Exploded view of all components except the housing



TRL-7 Design allows up to four power layers to be controlled from a single control layer (not shown)

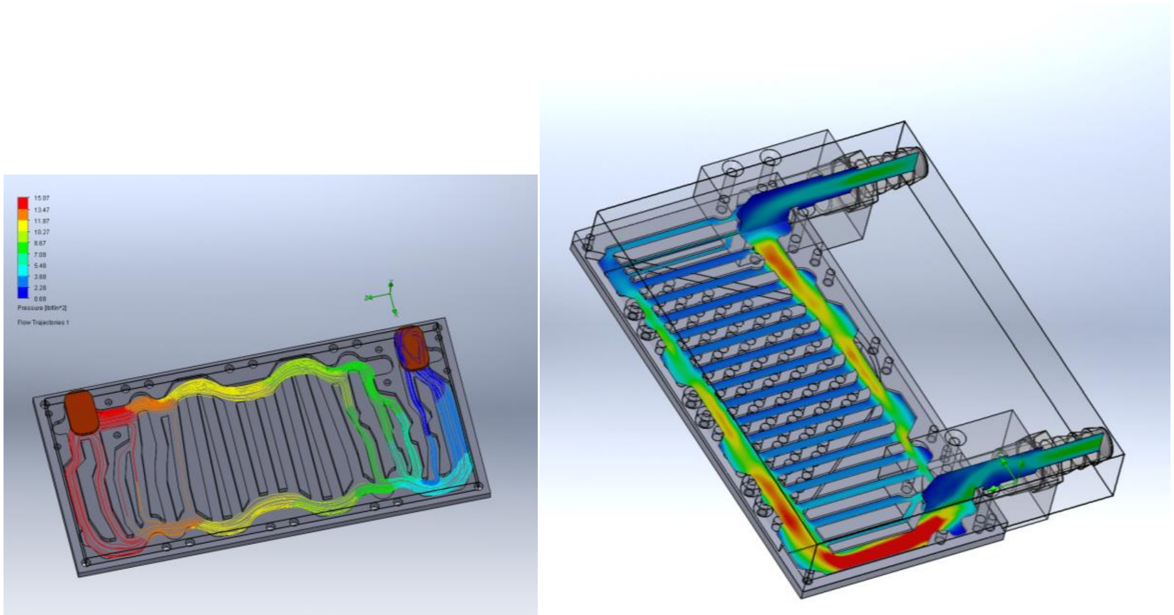
4. FEA Heatsink Optimization:

An important part of the TRL-7 design is the novel 2-sided heat-exchanger, which allows coolant to cool both the IGBT's and the air within the sealed power-layer enclosure. A cooling fan on the bottom of the thermal assembly blows cooled air directly onto the laminar bus, while IGBT's are mounted on the top of the assembly.



Heatsink, IGBT's, and cooling fan shown from top and bottom

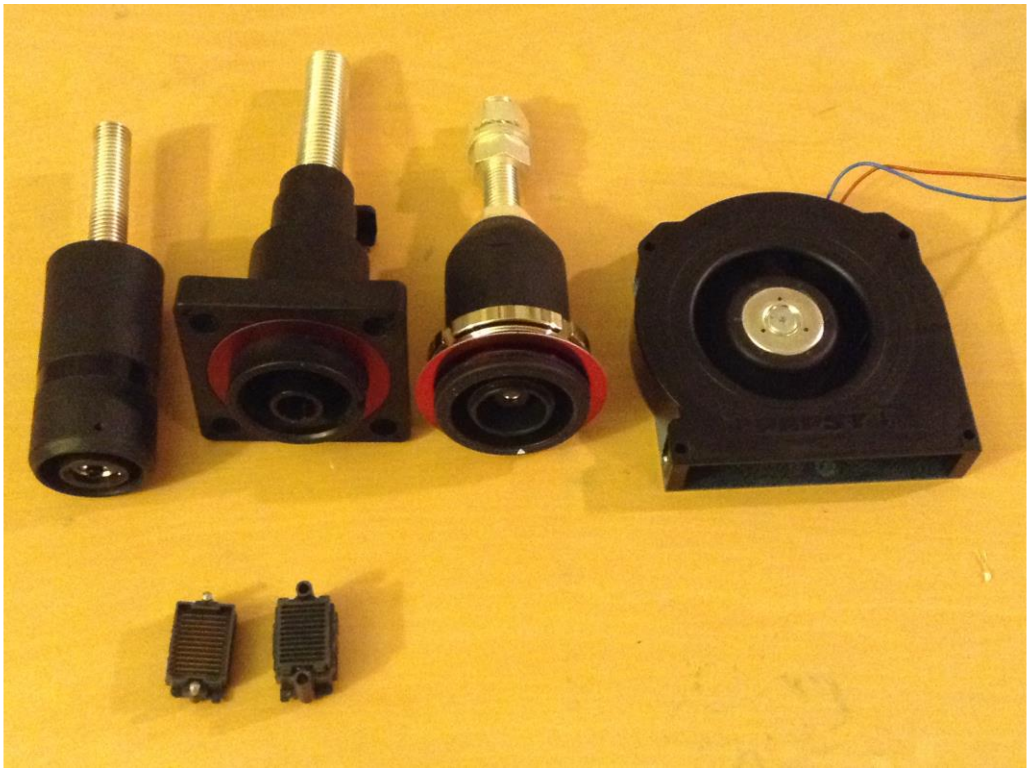
The heatsink has been optimized for oil flow using the SolidWorks FEA package. We began with a rough design and went through about fifty iterations to reach a design that resulted in uniform oil flow in all of the channels.



Coolant flow was optimized for oil using the SolidWorks FEA package: Rough design is on the left, final design is on the right.

5. Actual Components:

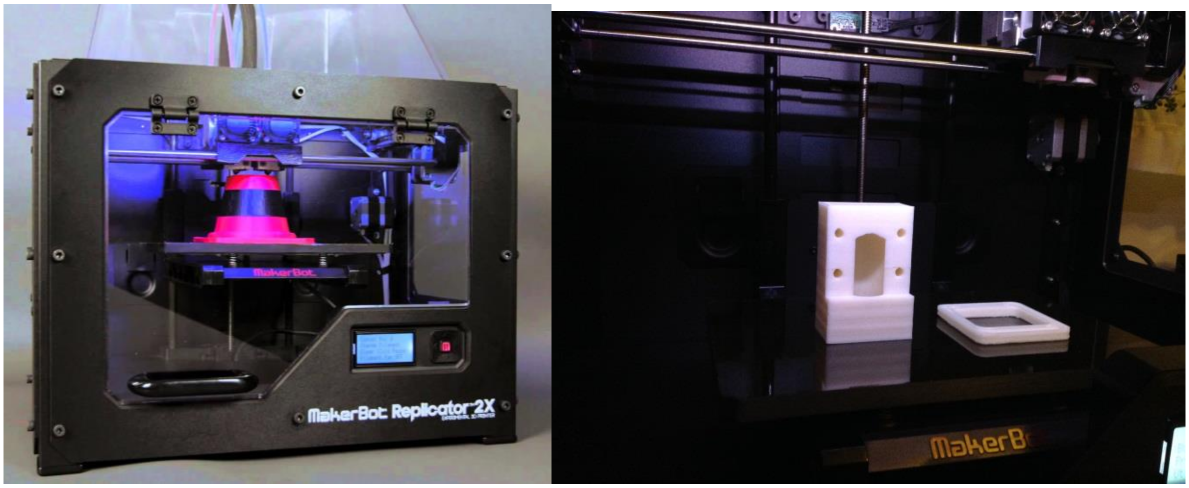
   For the TRL-7 inverter, a great deal of time has gone into selecting electrical and mechanical components. We are especially happy with the high current connectors from Multi-Contact, the low-profile cooling fan, and the high-density data connectors from Molex.



Samples of actual components to be used in the TRL-7 design.

6. Rapid Prototyping / Fabrication Technology:

One challenge we have faced during the TRL-7 design has been the need for a number of precision internal components with complex geometry such as PCB standoffs, coolant piping, sealed grommets for electrical connections, and many others. Traditionally these parts would have required complex machining or injection molding, and would not have been producible in-house. 3D printers, however, provide a high-tech solution to this problem which will save us time and money and provide both prototype and low volume production capability for all complex plastic components. After exploring many options, we chose the MakerBot Replicator 2X.. The MakerBot builds parts layer by layer by extruding plastic in precise amounts. The process, known as Fused Filament Fabrication (FFF), produces very strong plastic parts which can be used directly in our design.



Left: The MakerBot 2X, Right: TRL-7 Parts hot off the press and ready to use!

The 3D printer will pay for itself in shop time and in costs for parts we would otherwise have to outsource for our TRL-7 system. The MakerBot straddles the market between hobbyist and industrial machines.

7. EPA Compliance:

   EPA compliance is an important consideration as we look towards commercializing our technology. To this end we hired an EPA emissions consultant to help guide us through the daunting labyrinth of regulations and unfamiliar terms. After consultation, report reading, and research we can report the following:

1) Ideally we would use a variable speed marine auxiliary engine. Such engines are certified with a C1 test cycle.
2) At present no company manufactures a Tier 3, C1 tested, marine engine – though John Deere is working towards certification.
3) It is legal to marinize a non-road engine such as a tractor engine because they have a test cycle slightly more strict than C1. Marinization must not alter emissions.
4) To be legally installed on board a vessel, the exhaust manifold and turbo must be heat shielded. This is normally done with a water jacket. However, this alters turbo performance and emissions, so, some other form of heat shielding must be put in place. There are several heat shield options and we have a low-cost candidate which we will test in our DE Bus testbed.

Work for Next Quarter

1) Continue TRL-7 Design and begin construction of the inverter
2) Design the DE bus test-bed
3) Select and purchase a diesel engine for the DE test-bed
4) Select and purchase generator head and propulsion motor for DE test-bed